North Pacific Acoustic Laboratory and Deep Water Acoustics

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Award Number N00014-13-1-0053
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LONG-TERM GOALS

The ultimate limitations to the performance of long-range sonar are due to ocean sound speed perturbations and the characteristics of the ambient acoustic noise field. Scattering and diffraction resulting from internal waves and other ocean processes limit the temporal and spatial coherence of the received signal, while the ambient noise field is in direct competition with the received signal. Research conducted in the North Pacific Acoustic Laboratory (NPAL) and Deep Water Acoustics programs at the Applied Physics Laboratory (APL-UW) is directed toward a complete understanding of the basic physics of low-frequency, long-range, deep water, broadband acoustic propagation, the effects of ocean variability on signal coherence, and the fundamental limits to signal processing at long-range that are imposed by ocean processes. The long-term goal of this research is to optimize advanced signal processing techniques, including matched-field processing and adaptive array processing methods, based upon knowledge about the multi-dimensional character of the propagation and noise fields and their impact on long-range ocean acoustic signal transmissions.

OBJECTIVES

The scientific objectives of the North Pacific Acoustic Laboratory and Deep Water Acoustics research are:

1. To study the spatial and temporal coherence of long-range, low-frequency resolved rays and modes and the dependence upon ocean processes, transmission distance, and signal frequency.
2. To explore the range and frequency dependence of the higher order statistics of resolved ray and mode arrivals and of the highly scattered finale observed in previous experiments.

3. To define the characteristics and trends, and determine the relative causes of low-frequency ambient noise on ocean basin scales.
4. To elucidate the roles of internal waves, ocean spice, internal tides, fronts and eddies in causing fluctuations in acoustic receptions.
5. To improve basin-scale ocean sound-speed predictions via assimilation of acoustic travel-time and other data into numerical ocean-dynamic models.
6. To fully analyze our experiment in the Philippine Sea, the results of which will support all of the objectives listed above.

APPROACH

APL-UW employs a combination of experimental measurements, data analysis, simulations, and theoretical development to address the objectives outlined above. These activities are funneled through two primary avenues. ***The North Pacific Ambient Noise Laboratory***, operated and maintained by APL-UW, provides a full-time laboratory for real-time acoustic measurements at a selection of basin-scale locations, the capability to test various transmission signals, and ambient noise (including marine mammals) measurements in the NE Pacific Ocean. The Laboratory consists of legacy SOSUS hydrophone receivers in the Pacific Ocean, and a data processing and archive center at the Applied Physics Laboratory.

The second avenue includes highly focused, comparatively short-term experiments.
We have completed a pilot study/engineering test and an experiment in the ***Philippine Sea*** called **PhilSea9** and **PhilSea10**, respectively [1]. See Figure 1. The principal elements of the APL-UW effort during the 2010 experiment were: 1) a 55-hour continuous transmission from ship stop SS500 at 500 km from the DVLA and a depth of 1000 m, 2) a tow of a CTD Chain along the path toward the Distributed Vertical Line Array (DVLA) from SS500, 3) a source tow at a depth of 150 m at ranges between 25 and 43 km from the DVLA through the region of a Reliable Acoustic Path (RAP) from the near-surface region to the water column bottom, 4) a series of CTD casts every 10 km from the DVLA back to SS500, and 5) a 55-hour continuous transmission from SS500 at a depth of 1000 m to the DVLA. The primary institutions participating in PhilSea10 were APL-UW, the Scripps Institution of Oceanography (SIO), and the Massachusetts Institute of Technology (MIT).

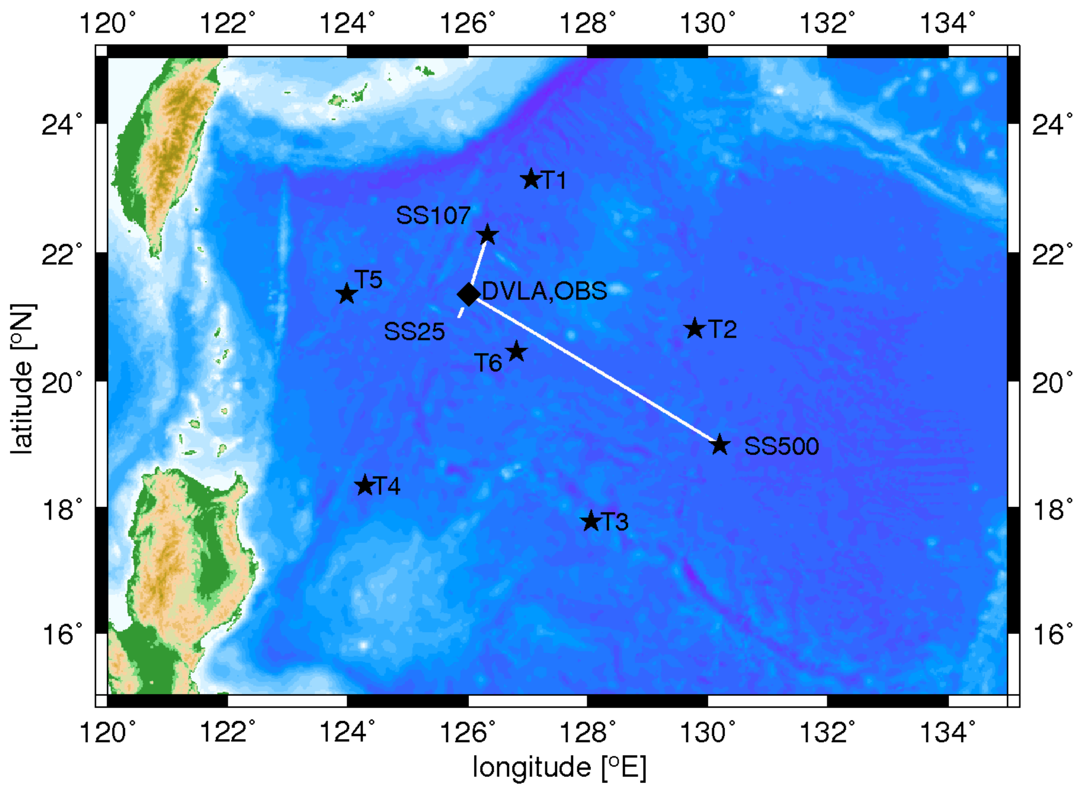

Figure 1. Principal activity locations for PhilSea9 and PhilSea10

WORK COMPLETED

I. Award Number N00014-13-1-0053

This post-doctoral award included analysis of a subset of the CTD measurements made at the DVLA during PhilSea10; design, construction, and completion of the broadband, 500-km-range MCPE simulations for center frequencies of 200, 300, and 81 Hz; some comparisons of the simulated data to measured data from PhilSea10; and modeling with broadband PE and Hamiltonian ray-trace codes, of propagation through internal-tide (IT) perturbed environments--relating to PhilSea09. Dr. White has prepared, and sent to co-authors, a manuscript that describes the IT results [2]. The IT work and conclusions are described in New Results Section I below.

II. Award Number N00014-14-1-0218

During this award period Dr. Mercer retired from his full-time position at the University of Washington and was re-appointed to a part-time position. In this new position, the Director of the Applied Physics Laboratory has assigned the following responsibilities: Dr. Mercer "will collaborate with APL scientists and engineers using expertise in deep water acoustics in the effort of processing and analyzing the acoustic transmissions from the PhilSea10 Experiment. As the PI, (Dr. Mercer) will

continue to play a role in the complete research process, including managing the project and technical reporting. These duties are completed through frequent collaborations with other members of the Acoustics Department. Additionally, (Dr. Mercer) will be providing advisement to graduate students as well as the national funding agencies and will also continue to supervise a post-doctoral research associate on the project as well."

Results of this effort are shown in a New Results Section II below.

NEW RESULTS

I. New Results Award Number N00014-13-1-0053

During PhiSea09 the acoustic intensity of one of the ray paths exhibited fades of up to 10 dB that lasted 18 and 12 h, respectively [3,4]. The modeling that is presented in this section was done to test the hypothesis that the internal tide (IT) caused these intensity fades. Theoretical considerations would lead one to believe that sound-speed inhomogeneity on scales as large as those of the tides should not affect the intensity (e.g. Desaubies (1978) [5]) - however, a viable alternative hypothesis is not obvious. The results of this work indicate that the IT could cause intensity fluctuations.

The IT environmental models consisted of plane waves traveling due East; the model included only the first vertical eigenmode associated with the frequency of the diurnal tide. The amplitude of this eigenmode was adjusted according to the variance of the vertical displacement measured on microCAT CTDs mounted on the DVLA during PhilSea09.

Displacement $\zeta(z, r, T)$ in the internal-tide model was given by

$$\zeta(z, r, T) = a\, \psi_1(z) \exp(i\, [\omega_1 T + \mathbf{k}_h \cdot \mathbf{r}])$$

in which $\psi_1(z)$ is the first mode of vertical displacement, a is the modal amplitude, ω_1 is the modal phase speed, $\mathbf{k}_h$ is the horizontal wavenumber vector, and $\mathbf{r}$ is the vector pointing from SS107 to the DVLA. The angle α that is listed in table 1 is the angle between the vectors $\mathbf{k}_h$ and $\mathbf{r}$. The evolution time of the internal tide was T, where

$$T \in \{1, 2, 3 \ldots 24\} \text{ (hour).}$$

Satellite measurements analyzed by Zhao (2014) [6] (see his figures 4 and 5) suggest that the Luzon Strait, which lies roughly 500 km due west of the site of the experiment, is the major source of the diurnal tide at the site of PhilSea09. That analysis took a time-average over multiple years, while PhilSea09 was conducted over a span of only approximately 2.5 diurnal periods; presumably, the relative contributions to the internal tide from various local bathymetric features varies with time (and, therefore, so does the tide's direction). We modeled the extreme cases of acoustic propagation anti-parallel ($\alpha = 180°$) and perpendicular ($\alpha = 90°$) to $\mathbf{k}_h$ to understand the effect of this uncertainty.

The presence of mesoscale variability at the location of the PhilSea09 pilot study was seen in SSH measurements and corroborated with the CTD timeseries recorded by the CTD instruments on the DVLA [3,4]. Single profiles from CTD casts made during PhilSea09 were low-pass filtered to include only scales larger than 100 m, and were then used as representative range-independent background profiles to be perturbed by the internal tides. Comparison of results between the different profiles

provided information about the uncertainties caused by a limited knowledge of the background sound speed.

A summary of the model environments used for both the Hamiltonian ray-tracing and the PE calculations is given in Table 1.

Table 1: Simulated environments. $\alpha_0 \approx 107°$, and is an estimate of the angle α during PhilSea09, made from ADCP measurements at the site of the DVLA.

Sim.	A	B1	B2	B3	C	D	E	F
Prof. #	0	4	4	4	5	10	16	20
α	α_0	90°	180°	α_0	α_0	α_0	α_0	α_0

Broadband propagation through perturbed range-depth ocean slices was calculated using the Navy Standard Parabolic Equation (NSPE) code. The arrival corresponding to path ID-3 was windowed out from the resulting timefronts and Fourier-transformed. The absolute square of the Fourier bin containing the 284-Hz contribution was taken to be the intensity—as was done in the case of the data from PhilSea09. The intensity vs. depth for profile c_4 at times T $\in\{1, 2, 3...24\}$ over the depth-span 800m to 1500 m is shown in Figure 2 below.

As can be seen in Figure 2, there is a depth-dependence of intensity over the span of depths shown, that is then translated in the vertical as the internal tide evolves in time. At a given receiver depth, this translation results in a changing intensity with time.

Some questions about the prediction noted in the previous paragraph occur to the authors: Is the direction of the internal tide relative to the direction of acoustic propagation (and thus the range-dependence of vertical displacement) important? Why is the acoustic intensity depth-dependent? Why does the variation of intensity with depth translate vertically with the internal tide?

The first question was answered by comparison of simulations B1 and B2: the angle between acoustic propagation and the internal tide doesn't significantly affect the magnitude of the intensity change at a given receiver depth.

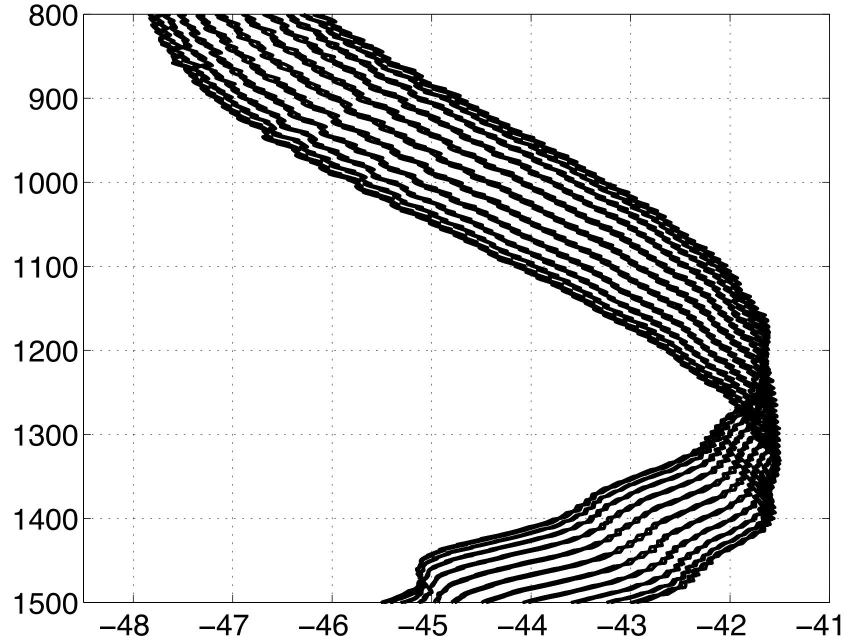

Figure 2: Time-series of intensity vs. depth predicted by the PE for profile c_4: $I_4(z,T)$, $T \in \{1, 2, 3...24\}$, simulation B3.

We will examine the results for profile c_4 in detail, but this profile is not unique in producing a depth-dependence of intensity. Figure 3 shows all the profiles used here at depths from 0m to 200m in the left panel, along with the resulting intensity vs. depth for each case in the right panel. All profiles, except the smooth, average profile, result in depth-dependence of intensity, which is translated with the evolution of the tide.

In order to answer the questions mentioned above, propagation was also calculated using a Hamiltonian ray-trace code that was developed previously by Dr. Frank Henyey. The parabolic equation (PE) is expected to contain all of the correct physics of the propagation, but what happens along the path is not revealed. When the ray-trace agrees with the PE, quantities associated with a given path that have been output all along the path then allow interpretation of the PE result.

For example, Figure 4 shows the ray intensity vs. depth for ID-3 in profile 4 in the left panel. The dashed line shows the intensity vs. depth for the smooth, average profile c_0. The right panel shows the third caustic for ID-3, which lies six km beyond the range of the DVLA. The "circle" marker shows the ray with the local maximum in intensity in the left panel, and the range and depth of that same ray at the deeper of the two cusps in the triplication in the right panel. Thus, the local maximum in intensity is associated with a cusp in the third caustic. There is no such triplication—and no local maximum in intensity—when profile c_0 is the background sound speed.

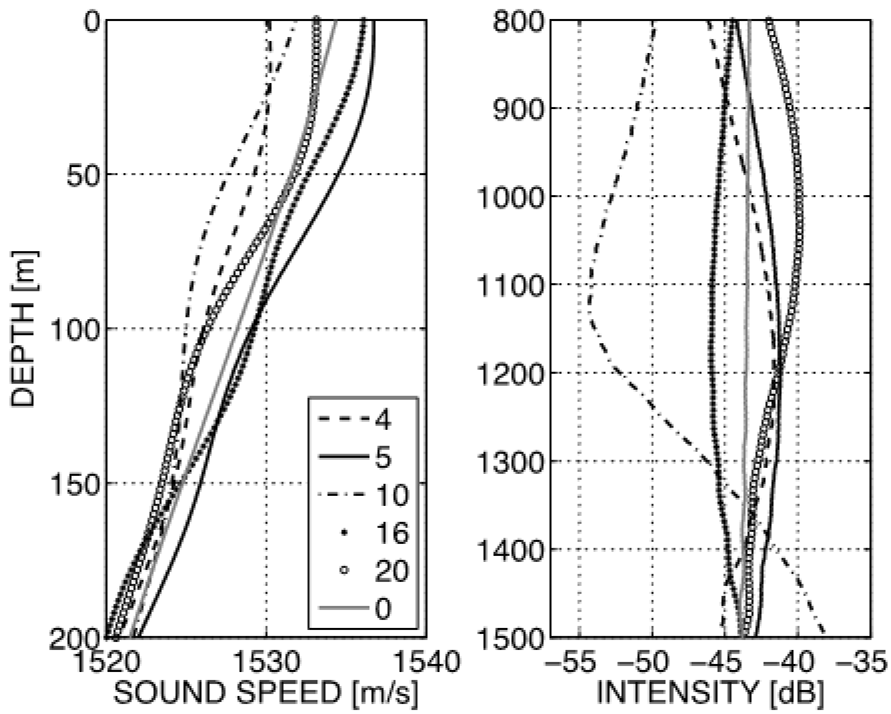

Figure 3: Left panel: Shallowest 200m of selected sound-speed profiles used as the range-independent background in IT simulations. Profile 0 is the smooth, average profile used in MCPE calculations in White et. al. 2013. The other profiles were low-pass filtered to remove scales smaller than 100m. Right panel: Intensity vs. depth shown from 800m to 1500m.

Figure 5 shows the changes in the position of the UTP of the ray with initial angle θ0 that occur with the evolution of the internal tide through times T ∈ {1, 2, 3...24}, in simulations B1 and B2 (RI and RD cases, respectively).

In the RI case, the UTP moves back and forth along a curve. In the RD case, the UTP traces out an ellipse. The same is true for the triplication discussed above: in the RD case, the cusp associated with the local intensity maximum traces out an ellipse with a maximum horizontal displacement of approximately 508 m, and a maximum vertical displacement of about 22 m. In the RI case, the maximum displacements are roughly the same, but the cusp translates back and forth along a curve.

In the RI case that is shown in the bottom panel of Figure 6, the endpoints of the curve along which the UTP translates are UTPs of the rays with extrema in arrival depth. These same rays are also those with maximum or minimum turning-loop-distance. Here, we have made a connection between vertical displacement of arrival depth and turning-loop-distance.

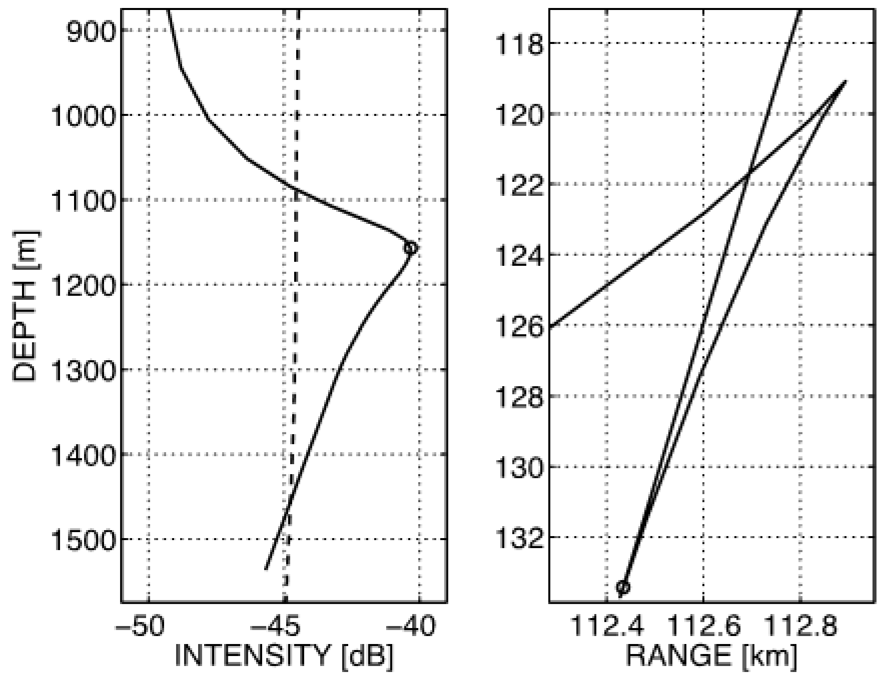

Figure 4: Intensity vs. depth at the range of reception (left panel) and range of the third caustic vs. depth (right panel) for path ID-3. This third caustic lies just beyond the reception range of 106,601 m. In the left panel, the dashed line shows the result for ID-3 with profile c_0 as the background, while the solid curve is the result for profile c_4, simulation B1, T = 1. The third caustic with profile c_0 has no triplication, and is not shown here. The black circle in both panels is the intensity (left panel) or caustic position (right panel) for the ray leaving the source at angle θ_0.

The mode-one displacement at the diurnal frequency (the mode is essentially the same at semi-diurnal frequency) has non-zero amplitude over the whole water column. The greatest amount of straining occurs above the sound-speed axis–though there is a smaller strain of the opposite sign below the axis, as seen in the right-hand panel of Figure 4. The total effect of this straining is to cause the average over depth of $|\partial_z S|$ to change sinusoidally with the phase of the tide. When the average $|\partial_z S|$ is reduced (increased), the average slope of the ray is also reduced (increased). If we consider a ray with some initial angle, but a reduced average slope, we see that the turning-loop-distance is increased. For a receiver at a fixed range, this means that a range is reached at a different point along the ray's trajectory, and therefore at a different depth—causing the vertical translation. The relationship is shown in Figure 6 for simulation B1, the RI case.

It was also found from one of the equations in the Hamiltonian formulation that the rate of change with range of ray spreading for perturbations to the initial angle (ray intensity is proportional to the perturbation in vertical distance between the rays for small changes in initial angle) is dominated by a term containing the second derivative with respect to depth of the slowness. The ray with the local maximum intensity is displaced along with a contour of the second derivative with depth of the slowness at the UTP.

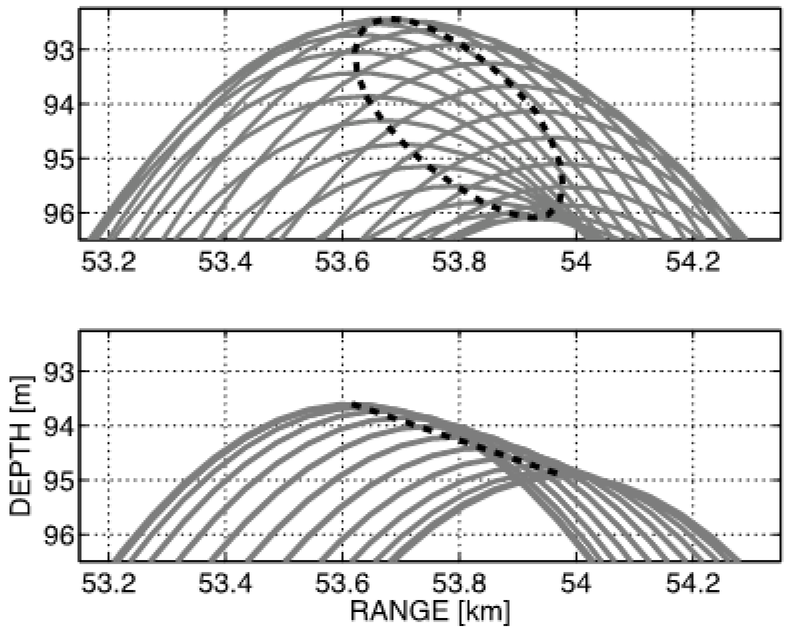

Figure 5: Evolution of the range and depth of UTP for ray ID-3 with initial angle θ0. Each curve shows the UTP of the ray with initial angle θ0 after propagation through a different sound-speed environment, at times T ∈{1, 2, 3...24}. The top panel: RD case (simulation B2); bottom panel: RI case (simulation B1). The dashed curves pass through the UTPs at successive times to illustrate the time-order.

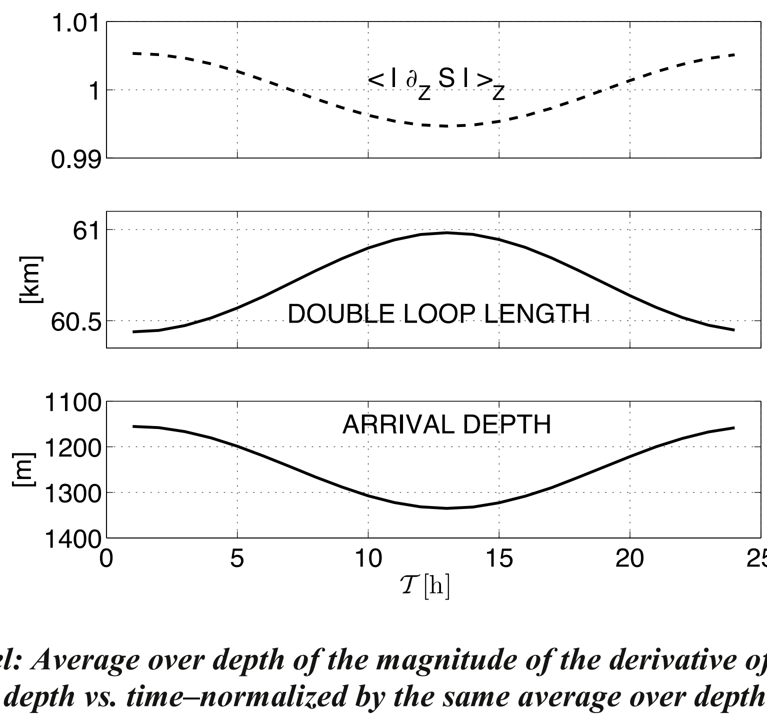

Figure 6. Top panel: Average over depth of the magnitude of the derivative of the slowness S (S = 1/c) with respect to depth vs. time–normalized by the same average over depth for the unperturbed profile. Middle panel: Double-loop distance in km for a ray with initial angle θ0 vs. time. Bottom panel: Arrival depth of the ray with initial angle θ0 vs. time.

Dr. White presented the results of the IT simulations and some 2010 MCPE-data comparisons in two talks at the 2014 Philippine Sea Data Workshop. The titles of the two talks were, “Preliminary comparison of MCPE to PhilSea10 measurements for scintillation index”, and, “The effect of the internal tide’s first mode on acoustic intensity in PhilSea09”.

II. New Results Award Number N00014-14-1-0218

New results for this grant have focused on co-authoring journal publications. Five manuscripts are in various stages of completion. Four of the papers address data from the Philippine Sea Experiment and the fifth is based on data from the Long-range Ocean Acoustics Experiment (LOAPEX) [1]. The titles and status of these manuscripts are provided below in the Publications Section.

IMPACT/APPLICATIONS

This research has the potential to affect the design of long-range acoustic systems, whether for acoustic surveillance, communication, or remote sensing of the ocean interior. The data from the NPAL network, and the special NPAL experiments, indicate that existing systems do not exploit the limits of acoustic coherence at long ranges in the ocean. Estimates of basin-wide sound speed (temperature) fields obtained by the combination of acoustic, altimetry, and other data types with ocean general circulation models have the potential to improve our ability to make the acoustic predictions needed for matched field and other sophisticated signal processing techniques and to improve our understanding of ocean variability.

COLLABORATIONS

A large number of additional investigators have been involved in ONR-supported research related to the NPAL project and participate in the NPAL Workshops, including Art Baggeroer (MIT), J. Beron-Vera (UMiami), M. Brown (UMiami), T. Chandrayadula (NPS), J. Colosi (NPS), F. Henyey (APL-UW), V. Ostashev (NOAA/ETL), R. Stephen (WHOI), I. Udovydchenkow (WHOI), A. Voronovich (NOAA/ETL), K. Wage (George Mason Univ.), Peter Worcester (Scripps), and others. In addition, we have begun close collaboration with Gerald D’Spain (MPL).

PUBLICATIONS

White, Andrew W, Frank S. Henyey, Rex K. Andrew, James A. Mercer, Peter F. Worcester, and Matthew A. Dzieciuch, John A. Colosi, “The effect of the internal tide’s first mode on acoustic intensity in PhilSea09”, 2014 PhilSea Data Workshop, Anza Borrego, CA

White, Andrew W., Andrew A. Ganse, Rex K. Andrew, James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch, John A. Colosi, “Preliminary comparison of MCPE to PhilSea10 measurements for scintillation index”, 2014 PhilSea Data Workshop, Anza Borrego, CA

Chandrayadula, Tarun K., Kathleen E. Wage, Peter F. Worcester, Matthew A. Dzieciuch, James A. Mercer, Rex K. Andrew, and Bruce M. Howe, "Mode tomography using signals measured during the Long-range Ocean Acoustic Propagation EXperiment (LOAPEX)," submitted to JASA.

White, Andrew W., Frank S. Henyey, Rex K. Andrew, and James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch, and John A. Colosi, "How the internal tide could cause intensity fluctuations," in preparation.

Andrew, Rex K., Andrew W. White, and James A. Mercer, "A test of deep water Rytov theory at 284 Hz and 107 km in the Philippine Sea," JASA, in press

Ganse, Andrew A., Rex K. Andrew, Frank S. Henyey, James A. Mercer, Peter F. Worcester, and Matthew A. Dzieciuch, "Deep fades without destructive interference in the Philippine Sea long-range ocean acoustic experiment," in preparation

Andrew, Rex K., Andrew Ganse, Andrew W. White, James A. Mercer, Matthew A. Dzieciuch, and Peter F. Worcester, "Low-frequency pulse propagation over 509 km in the Philippine Sea: A comparison of observed and theoretical pulse spreading.

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2. Andrew W. White, Rex K. Andrew, James A. Mercer, Frank S. Henyey, Peter F. Worcester, Matthew A. Dzieciuch, and John A. Colosi, “How the internal tide could cause intensity fluctuations” (sent to co-authors, intended for publication in JASA)
3. Andrew W. White, Rex K. Andrew, James A. Mercer, Peter F. Worcester, Matthew A. Dzieciuch, and John A. Colosi, “Wavefront intensity statistics for 284-Hz broadband transmissions to 107-km range in the Philippine Sea: observations and modeling”, J. Acoust. Soc. Am. 134, 3347 (2013).
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6. Zhao, Z. “Internal tide radiation from the Luzon Strait”, Journal of Geophysical Research: Oceans 119, 5434–5448 (2014).